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Structural Analysis in the Sympathetic Restoration and Conservation of the Gopinath Temple, Kathmandu, Nepal

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Abstract: The sympathetic restoration and conservation of built cultural heritage play a significant role in the management and preparedness for future climate scenarios by facilitating adaptive reuse, enhancing cultural resilience, preserving traditional knowledge, and boosting tourism. The importance of restoring damaged heritage sites after an earthquake drew international attention to Nepal after the 2015 Gorka Earthquake. UNESCO established an office in Kathmandu to promote the restoration of tangible and intangible heritage in the area. This included developing structural analyses of buildings with historical and cultural value that due to their nature cannot be intervened with the same methodology as modern buildings. In this paper, the case study of the earthquake-damaged Gopinath temple, is discussed. First, an initial visual inspection phase and the following diagnosis of the structure are discussed. Then, the results from a series of static and dynamic structural analyses performed to determine the safety level of the structure, together with a sensitivity analysis, are presented. A sympathetic intervention proposal capable of increasing the temple safety level and based on the addition of timber plates, has resulted in substantial improvements of the lateral behavior of the structure. The proposed intervention is deemed sustainable and able to increase the resilience of the temple in the face of future hazards.

Keywords: Nepal heritage conservation; Gorka Earthquake; Gopinath temple; structural analysis; safety level assessment; sympathetic intervention proposal; sustainability

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1. Introduction

The conservation of built cultural heritage is increasingly gaining recognition as a vital component in the pursuit of sustainable development goals [1–3]. The interplay between cultural heritage, including historic buildings, monuments, and cultural landscapes, and sustainability, embodies a profound overlap of social, economic, and environmental dimensions [4–8]. This interconnection offers a rich context for examining the potential contribution of cultural heritage conservation to sustainability and resilience in the face of global challenges such as climate change, urbanization, and socio-economic disparities [9–11]. Sympathetic restoration and conservation studies have the potential of elucidating the significance of conserving built cultural heritage in the context of sustainable development, underscoring the potential of these historical assets in achieving key sustainability goals, and fostering resilience within communities. Moreover, thoughtful preservation and adaptive reuse of heritage buildings can contribute to environmental sustainability, promote social cohesion, fuel economic growth, and enhance preparedness for future climate scenarios [12–14].

Particularly, unreinforced historical masonry buildings have demonstrated their vulnerability to different environmental and human-induced hazards [15]. Of special interest for the degree of damage caused on built cultural heritage and their frequent repetition, is the study of earthquakes, which have stroke on many occasions both in distant and recent history [16]. Many of the affected assets by this phenomenon are structures and monuments, possessing cultural values important for society and humanity. To develop effective seismic risk mitigation strategies, it is necessary to develop both new assessment procedures and new retrofit solutions that respect the cultural values and adhere to ICOMOS guidelines [17,18], while being sympathetic and sustainable. The analysis of such buildings is further complicated by uncertainties faced both in terms of material and modelling properties [19,20]. Another difficulty is the use of advanced numerical tools and the interpretation of the results, which require experience, knowledge, and understanding of the software. To cope with this issue, several numerical strategies have been developed, tested, and validated by different researchers [21]. Some examples are the so-called Equivalent Frame Models (EFM) [22,23], the Block-Based Models (BBM) [24,25], the Geometry-Based Models (GBM) [26–28], and the widely spread and adopted Continuum Homogeneous Model (CHM) [29–31].

Various researchers addressed the topic of retrofitting historical monuments using traditional and modern techniques while accounting for the above-mentioned difficulties and limitations. The first group of authors performed shake-table tests, on both unretrofitted and retrofitted specimens. Magenes et al. [32] tested unretrofitted two-storey stone-masonry buildings using both moderate and extensive strengtheninglep. Both interventions improved the building behaviour, but the research also proved that the desired effect can be achieved using innovative and non-intrusive retrofitting techniques. Guerrini et al. [33] tested both unstrengthened and strengthened unreinforced stone masonry, considerably improving the seismic behaviour by a non-invasive retrofitting intervention. A similar conclusion was reached by Vintzileou et al. [34] when performing a shake-table test on a three-leaf stone masonry building with wooden floors. Biaxial earthquake motion was applied incrementally, until the occurrence of repairable damages. Then, the specimen was strengthened by non-invasive interventions, primarily aimed at improving the connections between floors and walls and injecting the walls. Comparing the behaviour of the specimen under seismic excitations before and after strengthening shows that the intervention techniques improved the seismic behaviour of the structure.

A second group of authors proposed innovative strengthening techniques for retrofitting cultural heritage buildings both using numerical and experimental quasi-static methods. Mininno et al. [35] modelled both the in-plane and out-of-plane performance of Textile Reinforced Mortar (TRM) strengthened masonry walls. The study showed that the strengthening by using TRM layers largely improved the performance of the masonry walls both in terms of strength and displacement capacity. Arce et al. [36] studied the improvement of shear capacity on replicas of historical masonry walls through diagonal tension tests. The authors found an increase of up to 330% in peak shear strength by reinforcing specimens with two layers of carbon textile on both faces.

The case study presented in this paper is located in Kathmandu, the capital of Nepal; placed in the Himalayan belt. The area is an active seismic zone whose activity is caused by the convergent movement of the Indian plate into the Eurasian plate [37]. The interaction between these tectonic plates has caused major earthquakes that have considerably affected the country throughout its history [38]. The most recent event of considerable magnitude, 7.8 Mw, was the 2015 Gorkha Earthquake [39] that was the worst since 1934 [40]. It damaged over 800,000 buildings [41], including those part of the UNESCO World Heritage Site of Kathmandu Valley. The selected building presented in this paper corresponds to the Gopinath temple situated in Hanuman Dhoka, Kathmandu [42]. The objective was to understand the present state of damage in the temple by inspection and numerical analysis, followed by the design and numerical analysis of a retrofitting intervention that respected the temple's cultural values, practical limitations, and followed a sustainable approach.

The rest of this paper is organized as follows: In Section 2, the followed methodology to perform the study of the temple's history, conduct the visual inspection, and description of the developed

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numerical modeling, as well as the climate change considerations adopted, are presented. In Section 3, the results of the visual inspection, diagnosis, and structural analyses are highlighted. Besides, the retrofit intervention selected, and the safety level assessment of the temple achieved are also discussed within this section. The retrofitting intervention proposed and the effects on the structure are demonstrated using advanced numerical tools. Finally, in Section 4, conclusions based on the conducted work are reported.

2. Methodology

2.1. Historic Research

Historic research in the context of built cultural heritage conservation refers to the systematic investigation into the history and significance of a heritage building or site. This includes studying its origins, the purpose for its construction, the architectural styles and techniques used, changes made over time, and the socio-cultural context of its era [43]. This is the first activity recommended by the ISCARSAH guidelines on the analysis, conservation and structural restoration of architectural heritage [44]. Information about the temple's origin, phases of construction and modifications was obtained from the local library of the UNESCO office in Kathmandu. The collection included books about traditional architecture, and a report about previous interventions on this temple [45].

2.2. Visual Inspection

Visual inspection refers to the systematic observation and examination of a heritage building or site to assess its current condition, understand its construction and materials, and identify any signs of damage or deterioration [46]. The inspection campaign for the temple took approximately two days, starting from the exterior at the plinth level and documenting all the structural elements up to the highest level. The information was collected on paper and photographs which were later used to put together a damage assessment set of plans which describe in detail all the pathologies and structural deficiencies affecting the temple by the time of the visit (July 2017).

2.3. Numerical Modeling

The type of numerical analysis chosen for this study was the finite element method (FEM), following a macro-model approach [21]. The numerical analysis was performed using ANSYS version 17.1. Solid65 (iso-parametric tridimensional 8 node) elements were chosen to model the masonry walls as this type of finite element allows for the simulation of crushing and cracking behavior. Beam elements were chosen to represent the timber elements of the temple. Finally, roof mud and tiles weight were idealized as death weight and the corresponding load was applied directly to the masonry walls.

The structural analysis consisted of three main phases. On the first phase, the current state of the structure with no intervention was analyzed. This phase was meant to indicate whether the building needed any intervention or if failure was caused not because of a lack of capacity but because of the deterioration of materials or another external agent. Once the source of damage had been determined, the second phase was conducted. It dealt with the design of a sympathetic retrofit proposal that would increase the safety of the building against seismic actions while respecting sustainable principles. The final phase involved the structural analysis of the building including the retrofit proposal. The new numerical model results were validated, and it was verified that the subjacent structural problems of the temple were resolved by this intervention.

2.4. Climate Change Considerations

When considering the conservation of built cultural heritage, several environmental aspects are crucial. Of particular importance for the study case presented in this paper were the use of sustainable Materials and Practices, as the use of sustainable, locally sourced materials and energy-efficient practices in the conservation process can reduce the environmental impact of the designed retrofit intervention [47]. The proposed retrofitting techniques are based on the premise of resourcing

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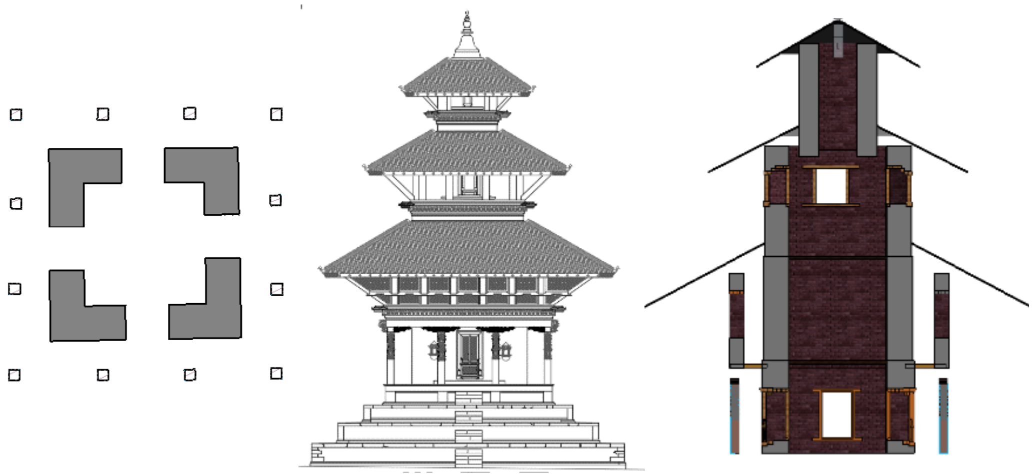
materials and expertise locally. Avoiding transportation of foreign components not only resulted in a high level of acceptance of the retrofit proposal but also in CO_2 savings related to the transport of foreign materials, tools, and workers.

3. Results and Discussion

3.1. Temple History and Characteristics

The Gopinath temple was donated as a state temple by a royal patron. Based on a study of the details and stylistics of the carved elements, it is believed the temple was built in the Malla period between 1641 AD and 1674 AD. There is no documentation of condition or repairs prior to 1934. Our knowledge of the temple begins after the entire structure collapsed to the plinth level during the Nepal-Bihar 1934 earthquake and was reconstructed two years later [48]. In 2004, another intervention campaign took place to address deterioration and restore some of its original strength [49]. Nevertheless, it suffered several damages during the Gorkha earthquake in 2015 [50].

Gopinath is a tiered roof temple (approximately 11m tall) standing upon a raised square brick plinth (approximately 3m high). The ground floor is composed of an inner unreinforced brick masonry wall with four door openings and a walkway between it and an outer timber colonnade. The masonry wall provides the main load-bearing system whereas timber elements form the main roof structure [51]. The temple's structure is shown in Figure 1.



(a) (b) (c)

Figure 1. Gopinath temple: **(a)** Plan view layout of ground floor; **(b)** Elevation view; **(c)** Cross-section view.

The brick masonry was constructed with mud mortar. Following the 1934 destruction, the lowest level was reconstructed with lime mortar for the ground level and mud mortar was used for the upper levels.

3.2. Visual Inspection Report

The most severe damage can be seen at the ground level masonry walls which have diagonal cracks, 1 to 30 mm wide, and crushing at the lower corners. The exterior masonry leaf at the ground level wall separated and moved out-of-plane up to 90 mm. The exterior wall at the first level shows severe out of-plane movement at the upper middle section and significant cracking as well. Timber connections were highly affected and show a permanent deformation with big openings at the joints. Timber columns show torsional movement and tilting as well. The temple has been propped and shored since 2015 as shown in Figure 2.

Figure 2. Gopinath temple current state (2017).

3.3. Finite Element Model and Structural Analysis

A 3D finite element model was created to study the structural response of the temple under seismic loads. A macro model approach, using isoparametric Solid65 eight-node hexahedral elements, was used to model the walls whereas the timber elements were modelled as linear elements. All simulations were performed using ANSYS®. The material model for masonry is based on the Willam Warnke theory [52] available in ANSYS® that allows the masonry to crack and crush.

The roof and tiles cover were not considered in the model and their weight was applied directly to the masonry walls. The ground floor wall base was modelled as simply supported. The boundary condition for the timber column was modelled as no lateral displacement combined with a spring that prevents penetration to the ground but allows uplift. The decision to use springs is based on the type of connections used in Nepali architecture where timber columns have a small wood pin carved at the base and are set in a stone base. This type of connection prevents lateral displacement but no uplift. The values adopted for the material mechanical properties are presented in Table 1.

Table 1. Mechanical properties used in the FEM model.

Property	Masonry	Timber
Density (kg/m^3)	1800.00	800.0
Young's modulus (MPa)	250.00	12500.0
Poisson´s ratio (-)	0.24	0.3
Uniaxial compressive strength (MPa)	1.00	-
Uniaxial tensile Strength (MPa)	0.05	-
Shear transfer coefficient for open cracks	0.30	-
Shear transfer coefficient for closed cracks	0.80	

3.3.1. Modal Analysis and Calibration of the Model

For this study, the numerical model was calibrated with natural frequencies measured in-situ by Japanese researchers from Tokyo National Research Institute for Cultural Properties [45] herby known as TNRICP, and experimental values measured in a similar temple (Radha Krishna temple in Patan, Kathmandu). The experimental frequencies reported for the first, second, and third natural frequencies of the building correspond to 2.0 Hz, 4.5 Hz, and 7.4 Hz (see Table 2).

Table 2. Modal frequencies for the Gopinath temple: experimental results and numerical model results before and after calibration.

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Natural frequency	Micro tremor results	Computer model before calibration	Difference in Percentage	Computer model after calibration	Difference in Percentage
Mode 1	2.00	4.63	131.50%	2.00	0.00%
Mode 2	4.50	9.51	111.33%	4.27	5.11%
Mode 3	7.40	-*	-*	7.31	1.22%

* It was not possible to capture the third modal frequency.

Literature sources on masonry built with mud mortar in Nepal use a value of modulus of elasticity (Young's modulus) of approximately 800 MPa. Using this value, the modal frequencies obtained in the analysis differ greatly from the ones obtained by ambient vibration noise tests. The modulus of elasticity of the model was lowered until the natural frequencies would be similar to the experimental values. Destructive tests were executed later on and confirmed that the Young's modulus for this type of mud masonry should be considered between 100 MPa and 250 MPa.

3.3.2. Pushover Analysis

The structural response is evaluated through its capacity curve which represents the value of the applied horizontal action in relation to the displacement of the control point. The top point of the structure was chosen as the control point. A pushover analysis was performed in the east-west direction which was the most vulnerable in terms of seismic performance for this building. Figure 3 shows that at approximately 0.09 g the increment of displacement starts to become non-linear, and above 0.17 g the displacement approaches the collapse condition and is used as an indicator of the structure capacity. Therefore, the capacity of the Gopinath temple in its damaged state with no additional reinforcement (unreinforced) is approximately 0.17 g. Figure 4 shows the total equivalent strain as a measure of crack opening, and compares it to the crack patterns found in the damage assessment phase. The model shows a good correlation even though the pushover analysis cannot fully replicate the complex load scenario that generated this type of damage [53].

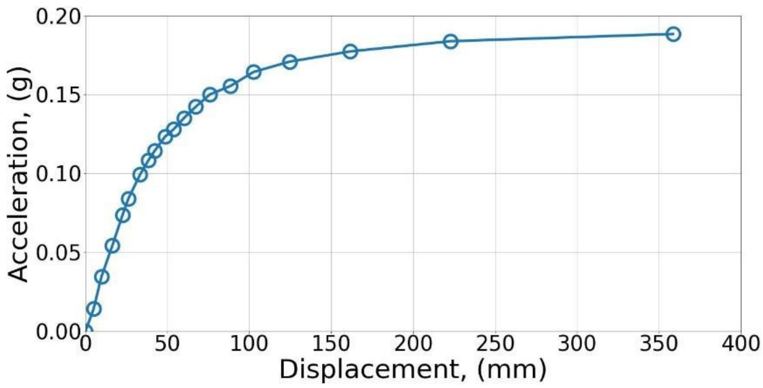

Figure 3. Pushover curve for the Gopinath temple without retrofit.

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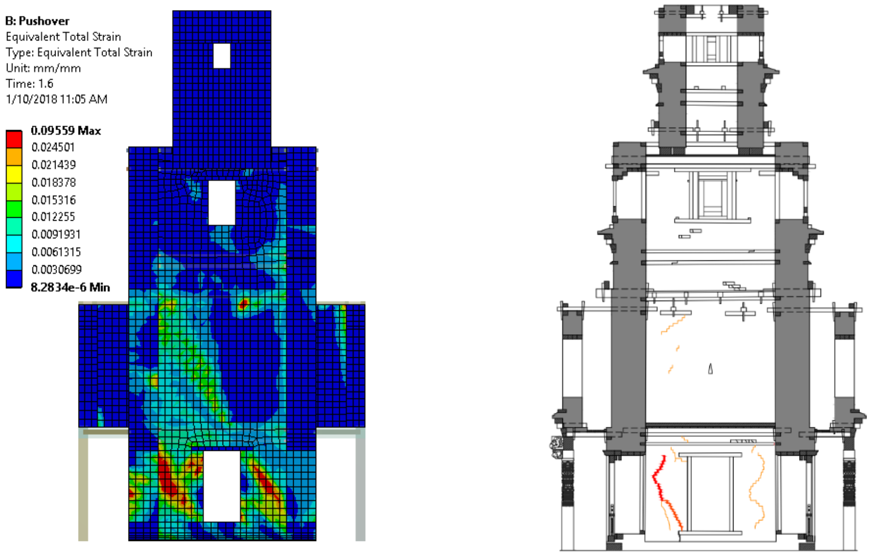

(a) (b)

Figure 4. Comparison of: **(a)** Total strain as a measure of crack development; **(b)** Real crack damage.

Due to the high seismic activity in the Kathmandu valley, The Nepal building code imposes high requirements of seismic design. The temple is required to prevent full collapse against earthquakes with peak ground accelerations up to 0.30 g [54]. The traditional way of reinforcing masonry structures in Nepal is based on the addition of timber plates. These plates are timber elements embedded in masonry walls (a line of bricks is removed and the timber plate installed in its place) to create rings. The timber rings (also known in literature as timber laces) provide shear capacity and improve the box behaviour of the building. Therefore, the presented proposal of repair is based on this traditional construction technique. The timber plates were modelled in ANSYS® as beam elements BEAM188.

The retrofit proposal (Figure 5) consists in adding three wall plates at the ground level and four at the first level in combination with an increase in masonry capacity from the current value (1 MPa in compression) to 2 MPa. Figure 6 shows the capacity curves for the temple in its damaged (original) and retrofitted state.

(a) (b)

Figure 5. Retrofit proposals for the Gopinath temple: **(a)** Original; **(b)** Timber and steel.

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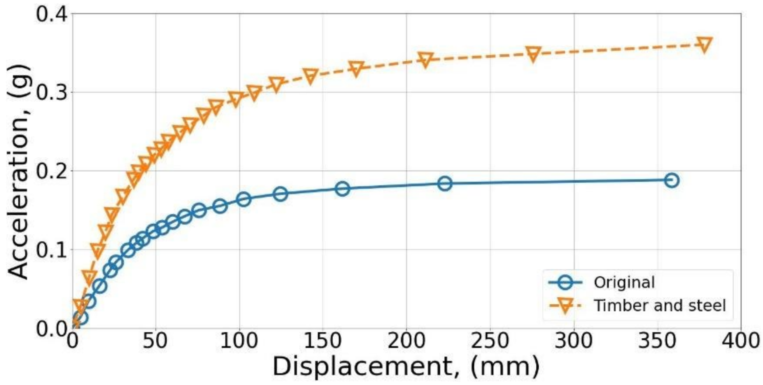

Figure 6. Capacity curves for the Gopinath temple before and after retrofit.

As can be seen from the Figure 3 in the case of the unreinforced model failure initiates for a seismic coefficient of 0.17 g. In the case of the reinforced model, as seen in the capacity curves in Figure 6, the reinforcement has proven to be effective, with failure initiation approximately around 0.3 g. This increase of the seismic coefficient in comparison to that for the unreinforced model is significant. The pushover analysis proves the intervention proposals to be effective, improving the building resistance to the horizontal forces, without a significant loss of ductility.

In contrast with western society where maximum conservation of the original fabric is a key consideration, some eastern cultures allow for the dismantling and reconstruction of building parts in order to repair or strengthen an important structure. In this proposal the ground floor would have to be rebuilt, the bricks are to be salvaged and reused and even the mud mortar recovered can be put to use again, the reutilization of local materials, the introduction of local timber reinforcing elements and the minimum addition of steel components results in an intervention which is aggregable for the community and drastically decreases the environmental impact associated with the transportation of foreign materials.

4. Conclusions

This paper dealt with the seismic response of Gopinath temple in Kathmandu, Nepal. First, analyses were performed on damaged and un-retrofitted structure to understand the remaining seismic capacity of the structure. The modal analysis allowed to calibrate the material properties for the FEM analysis by the selected modulus of elasticity that allows a good correlation between experimental and modelled modal frequencies also shows good correlation with material test results. A retrofit proposal was modelled, and a pushover analysis was executed. The analysis showed how the addition of timber plates can substantially improve the lateral behavior of the structure while adhering to sustainable practices by using locally available materials and craftmanship. Thus, it is concluded that the Gopinath temple structure can be provided whit a high level of safety by relying on traditional Nepali construction techniques and locally sourced materials.

In conclusion, the structural analysis of the Gopinath Temple in Kathmandu, Nepal, has proven to be instrumental in guiding its sympathetic restoration and conservation. The study has illuminated the intricate details of the temple's architectural design, the materials used, and the traditional construction techniques employed, all of which hold significant cultural value. It has also shed light on the structural vulnerabilities of the temple, enabling the development of targeted restoration strategies to retrofit the structure without compromising its historical integrity.

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Data Availability Statement: The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

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Conflicts of Interest: The authors declare no conflicts of interest.

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